Ultrafast Characteristics of InGaP–InGaAlP Laser Amplifiers

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***Abstract*— We characterize a visible, 670 nm, diode laser amplifier with respect to parameters of interest in short pulse generation and amplification. With a single pulse in the amplifier, we measure the differential gain and saturation energy of the amplifier, and changes in the optical spectrum of a pulse traveling through the amplifier. We also measure the ultrafast gain dynamics using a pump and probe technique. We find the ultrafast gain recovery time due to carrier heating is 400 fs ± 30 fs. Our results differ quantitatively from those reported for InGaAsP and AlGaAs amplifiers.**

I. Introduction

IN RECENT years, there has been considerable interest in the generation and amplification of short pulses in semiconductor materials and devices [1]–[20]. These lasers and amplifiers are being developed for fiber optic systems [1], optical sampling [2], and other novel applications [3]. The modulation response and the minimum pulsewidth achievable are of general interest. In this paper, we report experimental determination of several parameters pertinent to short pulse production and amplification in the InGaP material system.

The differential gain, differential index, and the saturation energy are among the more important material parameters for pulse dynamics [4]–[7]. In many systems, the minimum optical pulsewidth achievable with diode lasers is governed by the inverse of the differential gain and linearly proportional to the saturation energy. A higher differential gain leads to pulse shortening in both gain switched and actively mode-locked lasers [5], [6], [9], [10], at the expense of chirped pulses with lower output power. Using a single short pulse in the amplifier, we measure the dependence of the differential gain and saturation energy on the amplifier bias current and probe wavelength, and use the Kramers-Kronig relationship to calculate the spectral dependence of the differential index.

Another important parameter in short pulse generation and amplification is spectral distortion caused by the amplifier [7], [8], [20]. Nonlinearites, caused by gain compression mechanisms such as gain saturation or ultrafast carrier heating, have been shown to impart significant self-phase modulation on optical pulses as long as 10 ps, which leads to broadening and distortion in both the temporal and spectral domains [7], [8], [20]. Self-phase modulation is generally an undesirable effect in optical systems, however, it has been shown that spectrally broadened, linearly chirped pulses can be compressed using grating compensation, and the optical pulsewidth can be reduced [8]. In fact, for high-power amplification, a chirped pulse is preferred before amplification to avoid gain saturation [7], [8]. We measure the changes in the transmitted optical spectrum of the pulse as a function of amplifier bias current.

Using a pump and probe configuration, we investigate the subpicosecond gain dynamics of our amplifier. These fast gain transients may ultimately limit the minimum pulsewidth directly achievable from semiconductor lasers. These dynamics have received attention from both experimental [11]–[15], [20] and theoretical investigations [16]–[20]. The work reported to date has investigated either AlGaAs or InGaAsP.

Early work by Kessler *et al.* first described the rapid thermalization and subsequent cooling of carriers as the dominant gain compression mechanism [11]. The time constants associated with the gain recovery are dictated by the relaxation of the hot carriers back to thermal equilibrium with the lattice via phonon interaction. The effects of the carrier thermalization are also observable in the optical spectrum, and Delfyett has shown that carrier heating is one of the mechanisms leading to self-phase modulation [12].

Two color pump and probe experiments have also revealed new information on carrier dynamics unattainable with single wavelength experiments [13]. For example, the time evolution of carriers at energies higher than the pump wavelength has been shown to agree with the time constants associated with carrier heating, thus illustrating the importance of two photon processes and free carrier absorption [13]. Detailed experiments on both bulk and quantum well InGaAsP amplifiers have been carried out by Hall *et al.*, and their results are summarized in [14]. The gain has been shown to recover in 0.7 ps for bulk devices, and owing to a more selective density of states, the gain recovers in $\sim$1 ps for quantum well devices [14]. Recent results by Tessler have demonstrated an increase in the gain recovery time for lasers as compared to amplifiers [15]. This was attributed to the increased stimulated emission in the laser cavity.

Theoretical investigation of hot carrier effects were formulated by Gomatam and coworkers through a density matrix approach, where free carrier absorption was included *a priori* [16]. The density matrix approach has been extended to include

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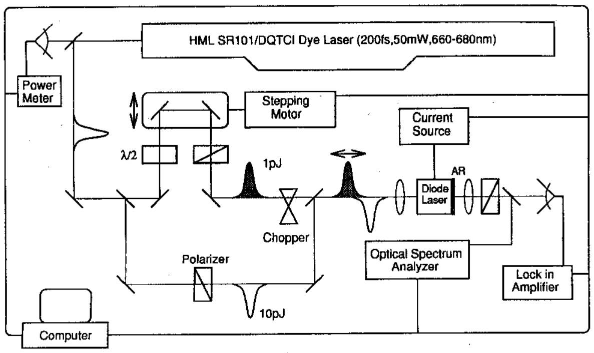


Fig. 1. Experimental configuration used to study ultrafast dynamics in visible wavelength semiconductor amplifiers.

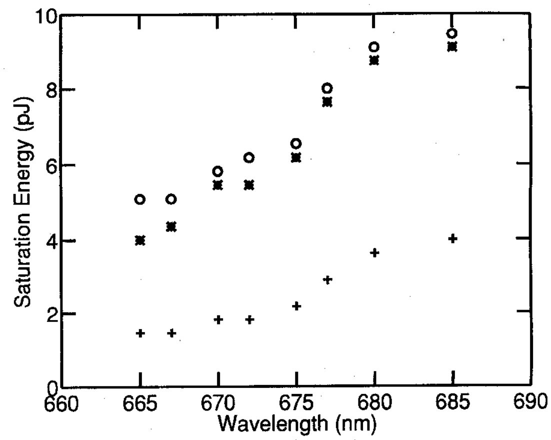


Fig. 2. Measured saturation energy as a function of wavelength for biasing currents of 70 mA (o), 50 mA (*), and 20 mA (+). Note the small change in saturation energy from 50 to 70 mA.

wave mixing effects [17] and spectral hole burning [18]. A rate equation analysis, including dynamic equations for both the electron and hole temperatures, has been shown to be in good agreement with experiments done on InGaAsP amplifiers [19]. Recently, a phenomenological model has been used to study pulse propagation in amplifiers. This approach includes both the temporal and spectral dynamics observed in amplifiers, and has been shown to be in agreement with experimental results for AlGaAs amplifiers [7], [20].

In this paper, we extend the spectrum of materials investigated to include InGaP. We find a faster gain recovery, and we consider the dependencies of the gain recovery with respect to band structure.

II. Experimental Setup

The diode used in our experiments is a channeled substrate, buried heterostructure InGaP–InGaAlP visible wavelength semiconductor laser (Hitachi HLP 6712G). In order to easily access both facets, the laser was removed from its package and mounted on a copper heatsink. Fabry-Perot effects were eliminated by antireflection ($R < 10^{-4}$) coating the front facet of the laser.

The experimental configuration we employed is shown in Fig. 1. The second harmonic from an acousto-optically mode locked Nd:YLF laser is used to synchronously pump and mode-lock a sulforhodamine 101 dye laser. When intracavity dispersion compensation and the saturable absorber DQTCI is introduced into the dye laser cavity, 200 fs pulses tunable from 660–680 nm are readily available. The spectrum of the dye laser pulse is constantly monitored on an optical spectrum analyzer in order to facilitate optimum, nearly transform limited pulses.

In the traditional pump and probe scheme, the dye laser beam is split into two, and one arm (probe) is delayed in time with respect to the other (pump). Two mechanisms of time delay are used. For long scans, a computer controlled stepping motor driven translation stage is used, with time resolution of 25 fs. For rapid data collection over a small (10 ps) window, a spinning glass block is used as the delay line. Here, the temporal resolution is better than 100 fs, and is limited by the dispersion of the pulse inside the glass. The advantage of the glass block is a much reduced data acquisition time (10 ms versus 10 min), and the ability to average many response functions, which helps remove power fluctuation noise arising from the dye laser. The power fluctuation, generally arising from fluctuations in the pump laser, is as much as 10% over the long times associated with scanning.

The polarization of the probe beam is rotated by 90° with respect to the pump. This in combination with good quality laser pulses helps to minimize any coherent interaction of the pulses inside the amplifier [21], [22]. In addition to polarization separation, the probe beam is encoded using an optical chopper, and lockin detection is used to further discriminate the pump and probe. The energy coupled into the amplifier is approximately 10 and 100 fJ in the probe and pump pulse, respectively. These levels are well below the saturation energy of the amplifier. We measure the probe transmittance as a function of time delay between pump and probe for various wavelengths, pulsewidths, and biasing currents. The data collection is controlled by a laboratory computer.

III. Single Pulse Dynamics

In this section, we report the wavelength and current dependence of the saturation energy, differential gain, and differential index of the amplifier, and the spectral distortion of a pulse caused by the amplifier. Here, the pump beam is blocked, and the probe transmittance is measured as a function of current, wavelength, and intensity. The behavior of the saturation energy is shown in Fig. 2. We define saturation as the input energy by which the available gain is reduced by a factor of two. The increase in the saturation energy with increasing wavelength and current is in qualitative agreement with results reported for InGaAsP amplifiers [23]. Also note in Fig. 2 that there is little change in the saturation energy between 50 and 70 mA, indicating that electrons are filling higher energy states with increasing current. Our experiments have not indicated a pulsewidth dependence in the saturation energy in changing from 2 ps to 200 fs pulses, which is contrary to results reported by Hall *et al.* [14], [24].

For short pulse generation in a semiconductor laser via gain switching or active mode locking, a large differential gain is desirable to achieve the minimal pulsewidth [4], [5], [10]. In Fig. 3(a) is a plot of the differential gain as a function of wavelength and current for both TE and TM modes. (The TE mode is polarized parallel to the plane of the junction, and the TM mode is perpendicular.) The differential gain is defined as the change in gain, g, divided by the change in carrier density, ΔN, where Δg is obtained from the change in probe transmittance induced by a change in injected carrier density. We find the differential gain is generally increasing with decreasing wavelength, and dg/dN is higher for TE modes than TM modes. For bulk devices, this is predominately due to an enhanced confinement factor for TE modes. This dependence has also been observed in AlGaAs amplifiers [10], and is believed to be the reason for the shortening of pulses from actively mode-locked systems with decreasing wavelength [9], [10]. The peak in the differential gain at lower currents for both TE and TM modes is from the carrier distribution, and as the current is increased, the peak shifts to lower wavelengths. In Fig. 3(a), the TM mode peaks after the TE mode because of the reduced confinement factor. With the measured differential gain spectra, we can calculate the differential index dn/dN by using the Kramers-Kronig relationship. Our results are shown in Fig. 3(b). We used a fitting procedure for the differential gain similar to the one described in [25].

The spectral dependencies of the probe transmission are shown in Fig. 5(a) for bias currents from 0–70 mA. The intensity axis is a log scale. The input spectra is identical to the spectra at 70 mA, the input pulsewidth is 200 fs, and the pulse energy is 1 pJ. The spectral dependence of the differential gain (Fig. 3(a)) and index (Fig 3(b)) induce changes in the optical spectrum of the pulse as it travels through the amplifier. The nonlinearity of the index caused by gain compression has been shown to lead to self phase modulation [8]. Delfyett *et al.* have investigated the temporal evolution of self-phase modulation, and described their results in terms of the well-known instantaneous frequency [12]. This instantaneous frequency leads to shifts in the peak of the optical spectrum, and the size of the shift is related to the amount of index change. In Fig. 4(b) is a plot of the intensity peaks in wavelength as a function of the bias current. The solid circles represent the highest intensity peak. From these two graphs, we can discern three regimes of operation. A self-phase modulation signature is observed in the spectra between 0 and 30 mA (absorption region), where the spectra is multiple peaked, spectrally broadened, and the peak wavelength shifts from higher to lower wavelengths. At transparency, 35 mA, the spectrum is essentially flat topped, and there is a small shift in the wavelength of the maximum intensity. Above 45 mA (gain region), the long wavelength peak dominates, and the spectra closely resembles the input. Note the change in the slope of the highest intensity peak in the gain region, and at high currents, the spectra is singly peaked, indicating that spectral distortion is caused by gain depletion and not by an intensity dependent refractive index [8], [12]. These gain and index dynamics effect the quality of pulses generated and amplified by semiconducting media. For example, the spectral evolution of mode-locked laser pulses has been examined by Delfyett *et al.* in a hybridly mode-locked semiconductor laser [7], and they have pointed out the importance of the optical spectrum in the dynamics of mode locking, particularly in a saturated gain medium.

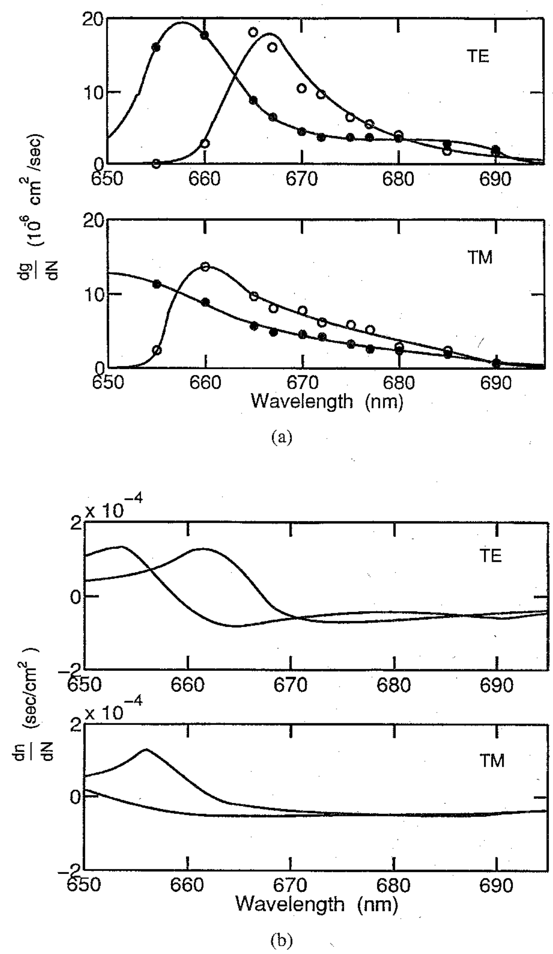
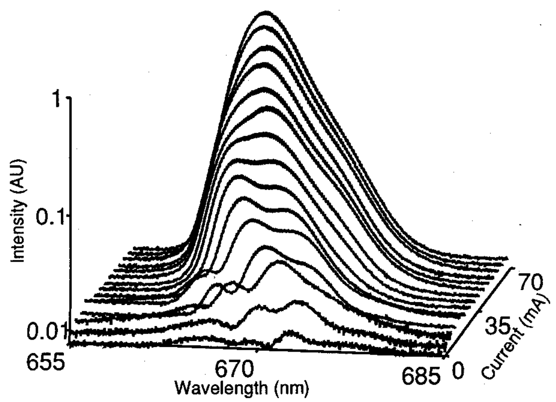


Fig. 3. (a) Measured differential gain as a function of wavelength for TE and TM modes, at 35 mA (o) and 70 mA (•). Note that the differential gain increases with decreasing wavelength, indicating that shorter pulses are possible in this regime. (b) Differential index spectrum calculated from the differential gain spectrum in Fig. 3 using the Kramer-Kronig relationship.

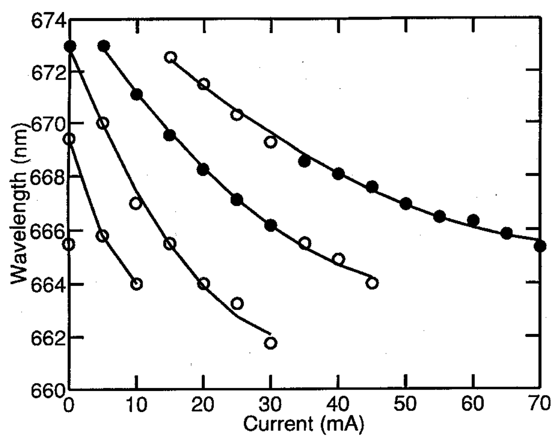
IV. Two Pulse Dynamics

The solid line in Fig. 5 is a typical response from our pump and probe experiments for an input pulsewidth of 225 fs. Here, the bias current is 70 mA, and the pump and probe wavelengths are both 670 nm, which is near the gain maximum of the amplifier. The pump and probe are exactly overlapped at zero time delay, and the probe is leading the pump for negative time delays.

The first feature of interest in Fig. 5 is the rapid decrease in the probe transmittance prior to zero time delay. This is a nearly instantaneous process that has been postulated to be due to two photon absorption, free carrier absorption, stimulated emission, and spectral hole burning [11]–[20]. We note here that the leading edge of the response closely resembles the autocorrelation of the input pulse which is the dashed line in



(a)



(b)

Fig. 4. (a) Transmitted probe spectra as a function of bias current in the amplifier, from 0–70 mA in steps of 5 mA. The vertical axis is a log scale. Spectral distortion is evident in the lower currents where the gain is heavily saturated. The input spectra is identical to the spectra at 70 mA. The input pulsewidth is 200 fs. (b) The highest intensity peak (•), and other spectral peaks (o) form Fig. 4(a) as a function of current in the amplifier.

Fig. 5. This indicates the system response is dominated by the rising edge of the pulse, and faster gain transients such as two photon absorption, stimulated emission, spectral hole burning, and free carrier absorption are obscured in this region.

The second feature to notice is the step change in gain for the probe lagging the pump. This is due to net stimulated emission of photons into the pump beam, and as a result, there is less gain available to the probe. Longer scans of our probe transmission response indicate the step change is flat after two picoseconds, and the transmission level returns to the value before the pump pulse in approximately the spontaneous emission lifetime (~1 ns).

The final, and most pertinent feature in Fig. 5 is the transient gain recovery from near zero time delay to 1 ps. This recovery time has been attributed to the cooling of hot carriers to the lattice temperature [11]–[20]. The highly excited carriers generated by two photon absorption and free carrier absorption thermalize, and heat the electron gas. The relaxation of the electron gas to the lattice temperature is the principle mechanism of the gain recovery. To measure this time constant,

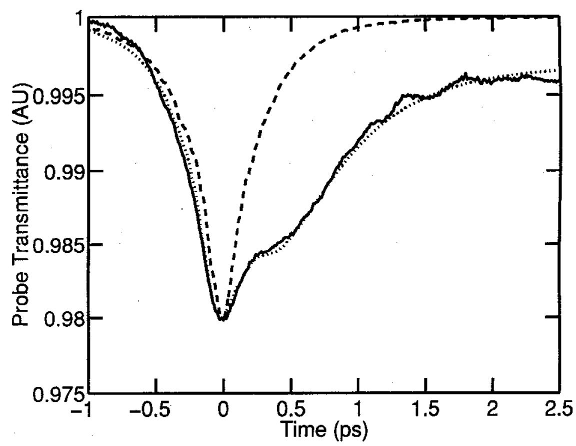


Fig. 5. Measured probe transmittance as a function of time delay between pump and probe (solid line), and fit obtained using an impulse response function (dotted line). The principle time constant used for the fit is $\tau_1 = 400$ fs. The dashed line is the input pulse autocorrelation ($\tau_p = 225$ fs). Here, the bias current is 70 mA and the probe wavelength is 670 nm.

we have used the impulse response model used by Hall [14], which was later derived by Mork [26]. The fit obtained is shown as the dotted line in Fig. 5. The specific equation used is

$$S(t) = \int_{-\infty}^{\infty} G^2(t')h(t-t')\,dt', \tag{1}$$

where $G^2(t)$ is the measured autocorrelation function and $h(t)$ is the impulse response function of the amplifier given by,

$$h(t) = u(t)(a_0 + a_1 e^{t/\tau_1} + a_2 e^{t/\tau_2}) + a_3\delta(t), \tag{2}$$

where $u(t)$ is the unit step function, $\delta(t)$ is the dirac delta function. In (2), the step change in gain is given by $a_0, a_1\exp(t/\tau_1)$ models the effect of carrier-carrier interaction, $a_2\exp(t/\tau_2)$ models the effect of carrier-lattice interaction, and $a_3\delta(t)$ models the instantaneous processes such as two photon and free carrier absorption. We find the best, least squares, fit to our experimental data is with $\tau_1 = 150 \pm 20$ fs, and $\tau_1 = 400 \pm 30$ fs time constant, and the delay in carrier heating is approximately 300 fs [14], [26]. We find this is appropriate for experiments conducted in the gain, transparency, and absorption regime, and for a modest range of operating temperatures (5–40°C).

Fig. 6 is a summary plot of our ultrafast pump and probe experiments. The probe transmittance is plotted as a function of time delay for bias currents of 20 (top curve), 40, 45, 50, 55, 65, and 70 mA, for pump and probe wavelengths of 670 nm. The probe transmission has been normalized to one at each current for the probe leading the pump. We note the 400 fs time constant is a reasonable fit for both the gain and absorption regimes. Of interest is the absence of a spectral hole burning signature observed by other researchers [13]–[15]. Here, the temporal resolution of our experiment is limited to 200 fs by the probe pulsewidth, and these effects are postulated to be on the order of 100 fs [13]–[19].

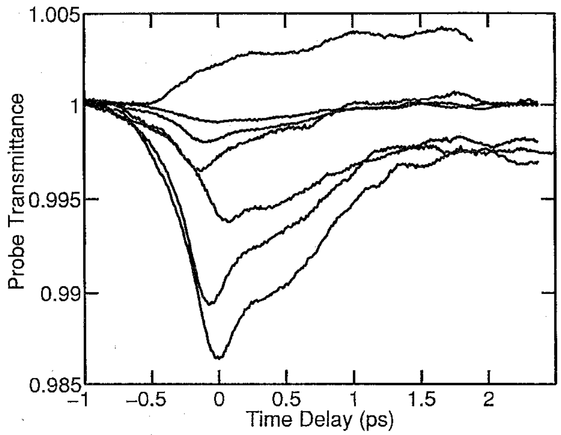


Fig. 6. Measured probe transmittance as a function of time delay between pump and probe for biasing currents of 20 (top curve), 40, 45, 50, 55, 65, and 70 mA. The pump and probe wavelength is 670 nm, and the probe pulsewidth is 225 fs in all cases.

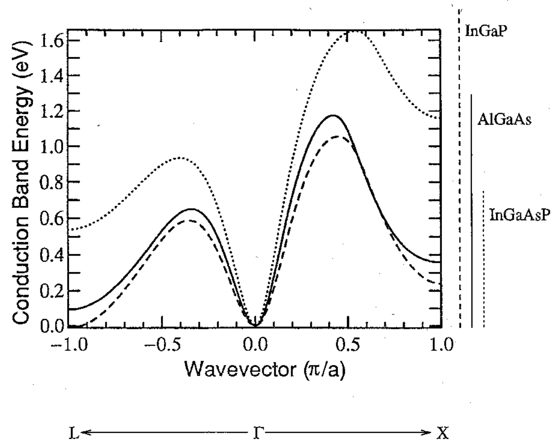


Fig. 7. Energy band structure of InGaP (dashed line), AlGaAs (solid line), and InGaAsP (dotted line). The x axis is the wave vector k in units of π/a. The Γ point is at $k = 0$, the X point is at $k = 1$, and L point is at $k = 1$. The lines to the right represent the material bandgap energies.

V. Discussion

We have presented a study of InGaP–InGaAlP amplifiers, and have reported several of the parameters of interest for short-pulse generation and amplification. In particular, we have measured the saturation energy and the differential gain as a function of both wavelength and current. A large differential gain will enhance the production of short pulses, at the cost of a reduced saturation energy. We have measured the differential gain spectrum and used it to calculate the differential index spectrum. The combination of the changes in the gain and index lead to pulse distortion in the amplifier, and we have measured the spectral distortion imparted on the optical pulse.

The ultrafast carrier dynamics, principally due to carrier heating, has been shown to recover with a time constant of 400 fs $\pm$ 30 fs, and is nearly independent of the probe wavelength and amplifier biasing current. Our ultrafast gain recovery time constant is significantly shorter than those reported for other material systems and structures [7]–[20].

This is the first study of femtosecond dynamics in InGaP–InGaAlP diodes, and the interpretation of the shorter time constant deserves some comment. The general shape of the response of the amplifier to pump and probe measurements appears to cross material boundaries, indicating that two photon absorption and free carrier absorption, leading to ultrafast carrier heating are the dominant gain compression mechanisms [11]–[20]. However, the cooling of the carrier distribution is influenced by the physical properties of each material. In Fig. 7 is a plot of the conduction band energy for $In_{0.53}Ga_{0.47}P$, $Al_{0.1}Ga_{0.9}As$, and $In_{0.6}Ga_{0.4}As_{0.85}P_{0.15}$. The energy bands were calculated using the sp3s* model [27]. The curves have been normalized to the conduction band edge for each material. The salient feature of this graph is the difference in the Γ point energy located at $k = 0$, and the X point energy located at $k = 1$, and the L point energy located at $k = -1$. The L point energy for InGaP is 100 meV less than AlGaAs, and 550 meV less than InGaAsP, while the X point energy is 100 meV less than AlGaAs, and nearly 1 eV less than InGaAsP. More importantly, the L point and Γ point energies in InGaP are on the same order. Hence, the L valley may provide a reservoir of electrons to scatter into the Γ valley. This may indicate that L-Γ and X-Γ scattering is more predominant in filling vacant states in the band minima for InGaP. This intervalley scattering time has been measured in GaAs to be on the order of 50 fs [28]. Finally, note that the photon energy for InGaP is much larger than the conduction band maximum, as indicated by the lines to the right of Fig. 7. This is not the case for InGaAsP and AlGaAs, which indicates that free carrier absorption may play less of a role in the gain dynamics of InGaP.

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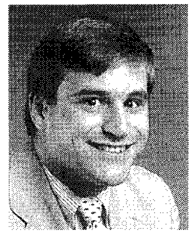

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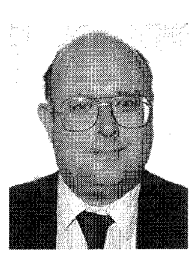
Dr. Klimeck is member of American Physical Society, Eta Kappa Nu, and Tau Beta Pi.



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His thesis research concerned the theory of the electronic structure of semiconductor heterojunctions. He continued this work in a post-doctoral position at the University of California at Santa Barbara. In 1977, he joined the Central Research Laboratories of Texas Instruments, Incorporated, where at first he did experimental and theoretical work in GaAs MESFET's. He contributed to the development of GaAs bipolar transistor IC's and more novel, vertically structured GaAs FET's. While at TI, he also worked on quantum effect heterostructure devices, contributing to the conceptual design and evaluation of tunneling devices. As a part of this work, he developed several theoretical approaches to the simulation of tunneling devices, including both rapid response design aids and more comprehensive physical models. In 1990, he became a Professor in the Electrical Engineering program at the University of Texas at Dallas, where he has continued the development of simulation and design tools for heterostructure devices. In 1995, he was appointed Head of the program.

Dr. Frensley is a member of the American Physical Society. He was Associate Editor of TRANSACTIONS ON ELECTRON DEVICES from 1983 to 1986.